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Understanding the fracture phenomena in inhomogeneous rock samples and ionic crystals, by monitoring the electromagnetic emission during their deformation

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Abstract

The electromagnetic (EM) activity observed before earthquakes has received a lot of attention of the scientific community. Various aspects have been proposed in order to interpret these observed EM phenomena, and the most plausible interpretation is based on the microfracturing electrification. The scope of this paper is the laboratory investigation of this aspect by carrying out laboratory experiments for the detection of EM emission from rock samples and other crystalline materials under uniaxial compression. This paper reveals physical processes that occur in the compressed material, in the microscopic scale, resulting in the observed macroscopic EM phenomena. It was experimentally verified that (a) an abrupt microcracking event generates temporally varying EM field, not only in piezoelectric materials but in non-piezoelectric ionic crystals as well. This implies that the EM generation mechanism is not necessarily of piezoelectric origin. (b) In the presence of a large number of microfractures, each one of them essentially acts as an elementary emission source and thus the resulting spectrum is correlated to the spectral content of each individual pulse and (c) the microcracking process might display criticality.

1. Introduction

The electromagnetic activity that is detected during the deformation and before failure of inhomogeneous materials, such as rocks, is of particular interest. This electromagnetic emission is detectable not only in the laboratory but in geophysical scale as well. Numerous laboratory experiments have been carried out to detect and identify the existence of acoustic and electromagnetic emission during deformation of crystalline materials and rocks (Nitsan, 1977; Gokhberg et al., 1982; Yamada et al., 1989; Hadjicontis and Mavromatou, 1995; Mavromatou and Hadjiconts, 2001). On the other hand, VLF to VHF electromagnetic activity has been reported resulting from seismic activities in the earth's crust (Hayakawa and Fujinawa, 1994; Eftaxias et al., 2001). Microfracturing electrification is discussed as a possible explanation of electromagnetic emissions observed before earthquakes (Molchanov and Hayakawa, 1995). It is unfortunately impossible to follow the evolution of a preseismic process in the lithosphere by directly monitoring the stress variations. However, it seems possible to estimate the evolution of a seismic activity by conducting field experiments of monitoring the accompanying electromagnetic activity in various frequency bands. It is obvious that laboratory experiments of uniaxial compression of inhomogeneous rock samples, with simultaneous monitoring of the electromagnetic emission before its complete failure, could propose appropriate field experiments.

2. Experimental apparatus

The experimental apparatus consists of

(a) The mechanical system for uniaxial compression.
(b) Three sensors. (i) a small broadband electrical antenna for the detection of EM radiation. (ii) a mechanoelectric transducer for the detection of

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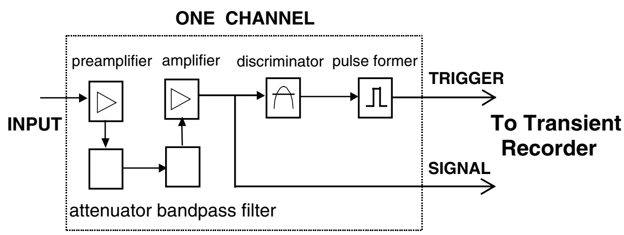

Fig. 1. Block diagram of one channel of the detection and monitoring setup—Analog unit.

acoustic emission mainly in the ultrasonic range and (iii) a load cell which converts the stress variations to electric potentials.

(c) The electronic device, the block diagram of which is depicted in Fig. 1. This device is the analog unit of the detection system. The complete system consists of two similar channels; one for the detection of acoustic and the other for the detection of electromagnetic emission in a frequency range from 1 kHz up to 1 MHz. The electric antenna feeds one of these channels while the mechanoelectric transducer feeds the other. The pulse forming circuit of this system is used to trigger the transient recorder.

(d) The transient recorder is a digital unit. The system is triggered only when we want to record with very high sampling rate acoustic or electromagnetic events of very short duration. It consists of two channels and its maximum sampling rate is 1 Msample/s. The two analog outputs of the aforementioned analog device feed the two channels of the transient recorder. Therefore, the two signals corresponding to the acoustic emission and to the EM emission are digitized and stored. The triggering level is selected according to the noise level.

(e) The memory recorder digitizes and records continuously (with a sampling rate of 20 ksamples/s) the signal of the analog input (Fig. 1), as well as the stress variations.

All the measurements are conducted in a shielded room (Faraday-cage) in order to eliminate the electrical noise. The maximum sampling rate limits the spectral analysis up to 500 kHz.

3. Experimental results

The experimental results can be summarized as follows:

Fig. 2 depicts the complete time evolution of the EM activity, as the stress changes under constant deformation rate from the beginning of the compression to the final failure. In the middle diagram of Fig. 2 it is shown that the failure of the sample lasts from about 3.65 to 5.4 s. The final failure of the sample is declared with three successive catastrophic major events, accompanied by dramatic increase of EM activity.

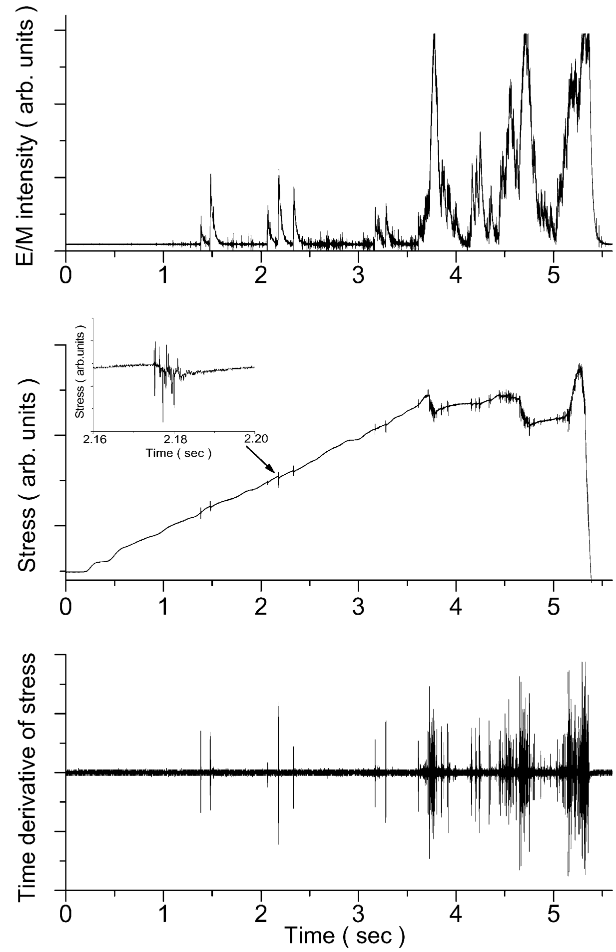

Fig. 2. The time evolution of EM field intensity (upper), stress (middle) and time derivative of stress (lower) up to the final failure of a granite sample (sampling rate: 20 ksamples /s).

Fig. 3 is a magnification of Fig. 4, from 3.50 to 3.80 s, giving us the possibility to observe the evolution in details and it pin-points the initiation of the microfracturing acceleration (boundary of areas a and c) by the abrupt increase of EM activity and by the stress fluctuations. The most important comment resulting from Fig. 3 is that beyond a critical value of stress, a dynamic uncontrolled process starts which inevitably leads to the final failure. This critical value is at the boundary of areas a and b and is accompanied by dramatic increase of EM activity and by significant stress drop.

Fig. 4 depicts a typical example of simultaneously recorded EM (lower) and acoustic (upper) time series during microfracturing activity in a granite sample. These signals have been recorded by the transient recorder with high sampling rate, 1 Msample/s.

Fig. 5 shows two pictures. The upper panel shows signals emitted from a granite sample and the lower

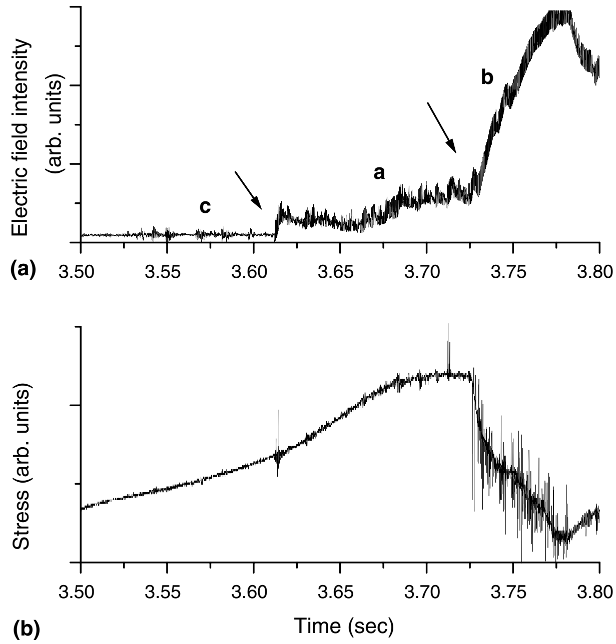

Fig. 3. Magnification of Fig. 4, from 3.50 to 3.80 s.

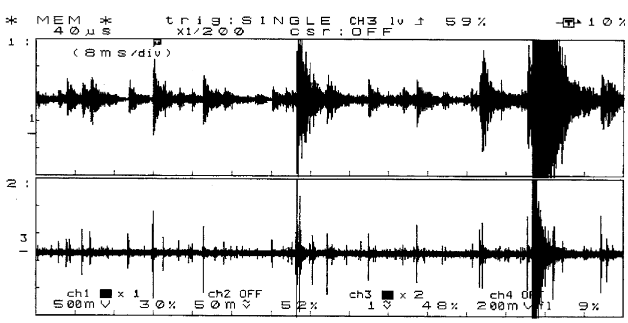

Fig. 4. Typical recording of a time series of acoustic emission (upper) and electromagnetic emission (lower) for a granite sample (sampling rate 20 ksamples/s).

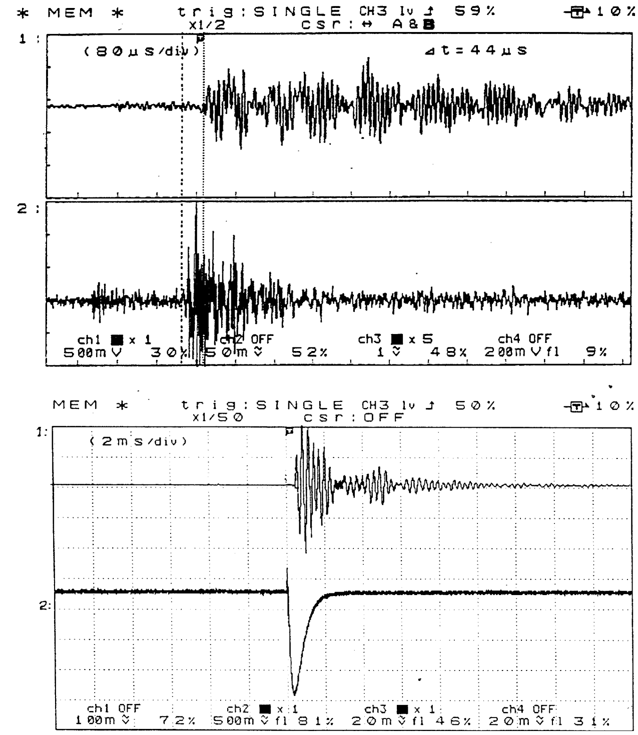

Fig. 5. Individual pair of an acoustic (1) and an electric (2) event (upper picture) associated to a microcracking event from a granite sample and from a LiF sample (lower picture) (Sampling rate: 1 Msample/s).

shows signals emitted from a LiF sample. In each picture an individual pair of an EM (1) and an acoustic (2) event is shown, associated to the same microcracking event. The time scale in Fig. 5 is magnified as compared with that of Fig. 4. The high sampling rate allows us to focus on each individual event of the time series with no loss of information. It should be emphasized that the acoustic event is the "signature" of one microcracking event. It must be additionally noted that the time delay (about 40 μs between the two cursors) of the two signals arrival time is due to their different propagation velocities. Taking into consideration the acoustic signal velocity and the propagation path, this time delay is acceptable and is in agreement with other researchers (Yamada et al., 1989). The experimental observations that were mentioned above, verify that a microcracking event cause the emission of an electromagnetic pulse.

Fig. 6, right, depicts the spectrum of an individual EM event associated to a microfracture while Fig. 6 left, depicts the total spectrum of a complete time series consisting of a large number of EM events. It should be noted the similarities of the two spectra.

4. Discussion and conclusions

(a) The simultaneous recording of the acoustic and electromagnetic pulses associated with the same microcracking event, is an undeniable evidence that the abrupt microcracking generates temporally varying electromagnetic field. This does not demand that the sample should be necessarily piezoelectric (Nitsan, 1977), because the phenomenon is also observed in no piezoelectric crystalline materials such as LiF.
(b) In the presence of a large number of microfractures, each one of them essentially acts as an elementary emission source and thus the resulting spectrum is correlated to the spectral content of each individual pulse. The latter is derived from the two spectra shown in Fig. 6. In other words, when the granite sample is in the microfracturing acceleration regime, it acts essentially as a transmitting element in the frequency band shown in Fig. 6. It should

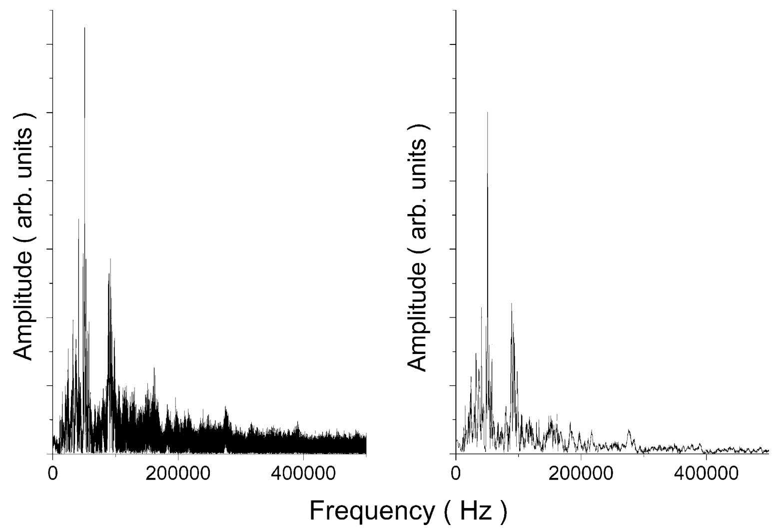

Fig. 6. (Right) The spectral content of an individual EM event associated to a microcrack opening in a granite sample. (Left): the total spectral content of the whole time series of EM activity. Note the similarities in the two diagrams.

be mentioned that the maximum sampling rate of 1 Msamples/s used in our experiment, limits the maximum frequency deriving from the spectral analysis up to 500 kHz.

(c) The experimental methodology used in this paper allows the monitoring of processes that occur during the deformation and failure process of a sample under uniaxial compression. This monitoring is based on the continuous recording of the electromagnetic emission. The electromagnetic pulses are the signatures of the physical processes happening in the microscopic scale. It should be clarified that when saying "catastrophic event", we mean an extended macroscopic damage due to the nucleation of many microcracks. One individual microcracking event is not considered as a macroscopically catastrophic event. It is obvious that according to the extension of the damage and consequent energy release, the events are characterized as minor or major ones. As shown in Fig. 2, we observe that the final catastrophic failure initiates with the first major catastrophic event, at about 3.65 s. Nevertheless, before this major event, other minor catastrophic events take place. The detail of such a minor event indicated by the arrow and enlarged within the picture, from 2.16 to 2.20 s, is also shown. It should be also noted that any EM activity is macroscopically observed even in minor catastrophic fractures. However, the sample still holds and there is no fragmentation yet. The stress keeps on increasing. The initiation of the process, which will possibly lead to the final failure, is marked by an abrupt increase of the intensity of the EM emission (see Fig. 3, boundary of c and a areas, at about 3.61 s). Additionally, more intense fluctuations of the stress are observed. It should be emphasized that if we stop compressing the sample before this particular moment, the failure evolution is halted, although the sample is "injured". On the contrary, if the deformation process continues, the stress reaches a critical value (Fig. 3 at about 3.72 s) and a first very strong catastrophic event appears, accompanied by a drastic increase of the EM emission and simultaneous stress drop. This event is the initiation of the unstable situation, which inevitably leads to fragmentation and final failure through successive catastrophic events. Beyond this stage, the deformed sample does not "resist" any more and the stress permanently drops after some large fluctuations. The aforementioned observations might lead to the conclusion that the microfracturing process might display criticality. A more detailed statistical analysis on the EM signals accompanying microfracturing could confirm the latter aspect.

(d) Another important comment on Fig. 2 is that the first time derivative of the stress is strongly "excited", when we observe EM emission bursts.

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